Signals and Circuits

ENGR 35500

Operational Amplifier

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Problems can be solved by Op-amp

- **Signals are too small**
- **Signals are too noisy**
- **Need to improve the compatibility of system (impedance)**
- **Need some special operations**

  Summers
  Inverters
  Comparator
  Differentiators
  Integrators

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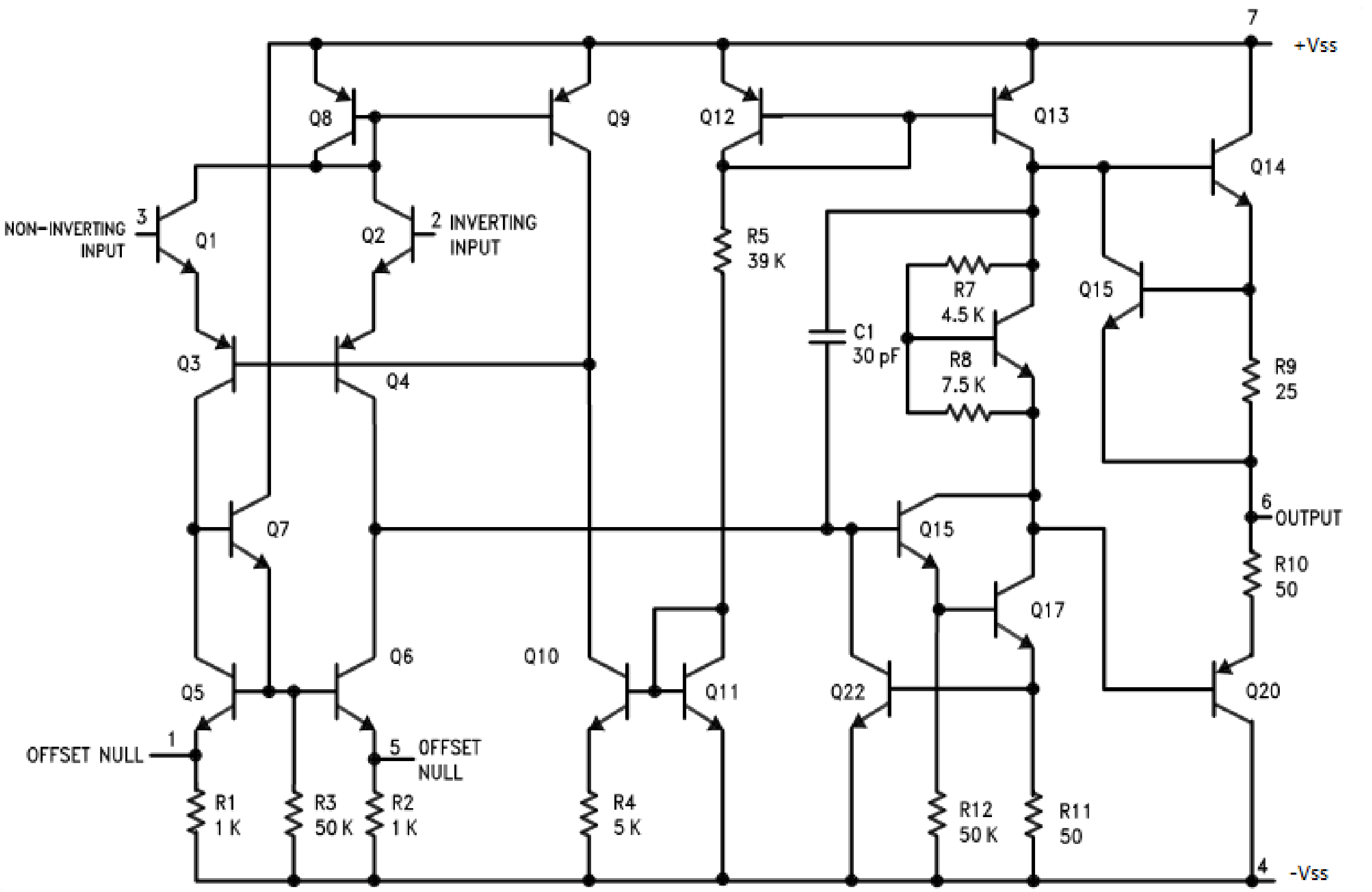
What is an Operational Amplifier?

An operational amplifier is a DC-coupled high gain electronic voltage amplifier with a differential input and usually, a single-end output. (Wikipedia)



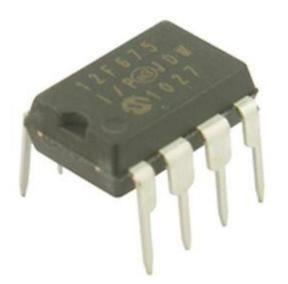


Fig. 1. Op-amp chip inside schematic representation

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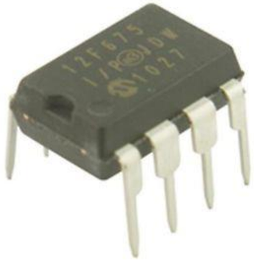

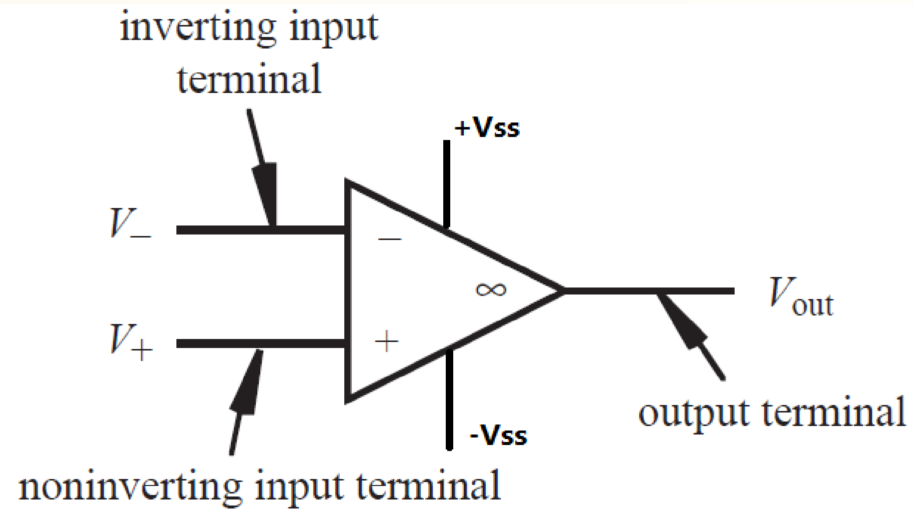

Fig.2. Op-amp schematic representation

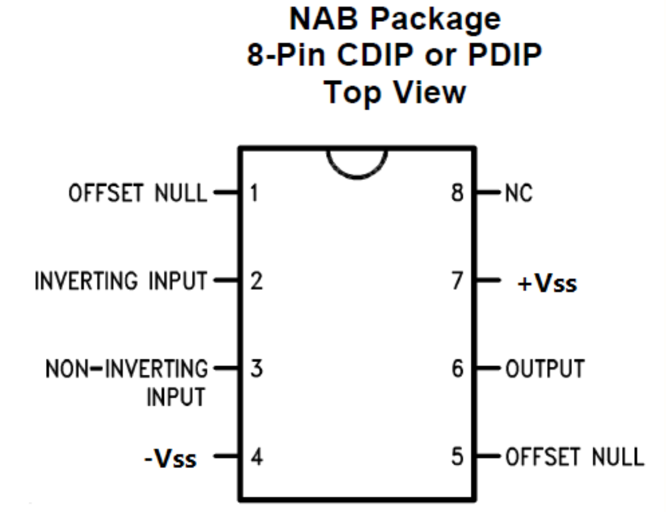

Fig.3. Op-amp schematic representation

What is an Operational Amplifier?

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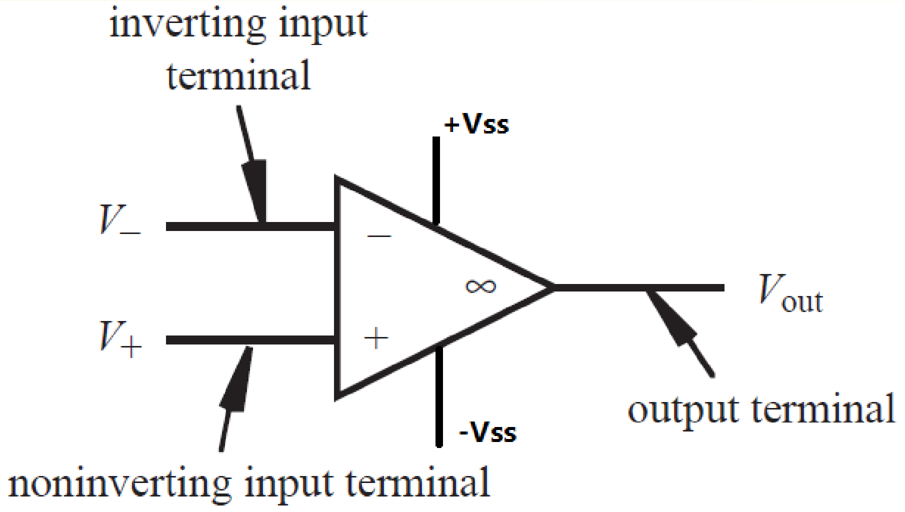

Fig.2. Op-amp schematic representation

$$V_{out} = (V_+ - V_-)A_v$$

$$A_v \rightarrow infinity\ (large\ number)$$

$$V_{out} \in (-V_{ss}, +V_{ss})$$

$$V_{out} = \begin{cases} +V_{ss} & V_+ > V_- \\ -V_{ss} & V_- > V_+ \end{cases}$$

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What is an Operational Amplifier?

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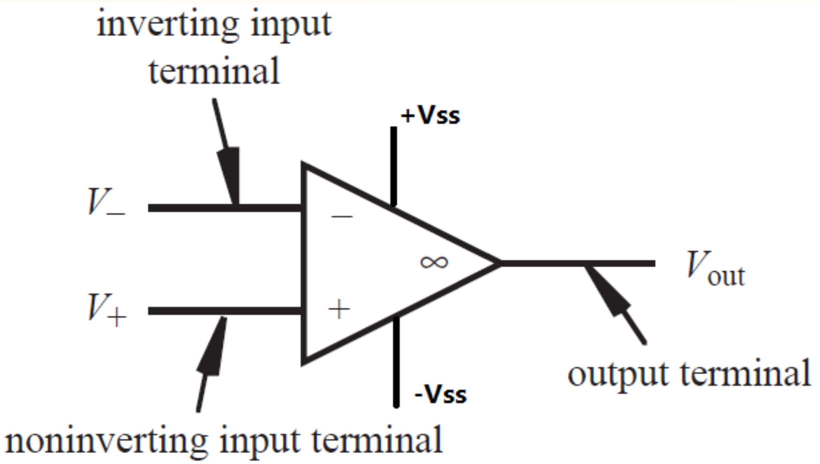


Fig.2. Op-amp schematic representation (open-loop)

VS

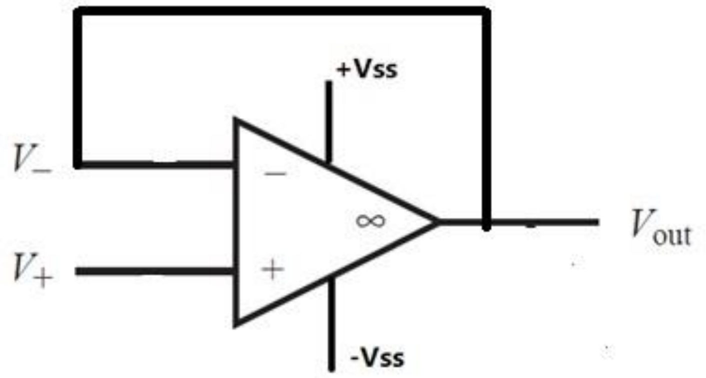


Fig.3. Op-amp schematic representation (closed-loop)

$$V_{out} = (V_+ - V_-)A_v$$

$$A_v \to infinity\ (large\ number)$$

$$V_{out} = \begin{cases} +Vss & V_+ > V_- \\ -Vss & V_- > V_+ \end{cases}$$

$$V_{out} = V_- = (V_+ - V_-)A_v$$

$$A_v \to infinity\ (large\ number)$$

$$V_{out} \in (-V_{ss}, +V_{ss})$$

$$(V_+ - V_-) \to 0\ (very\ small\ number)$$

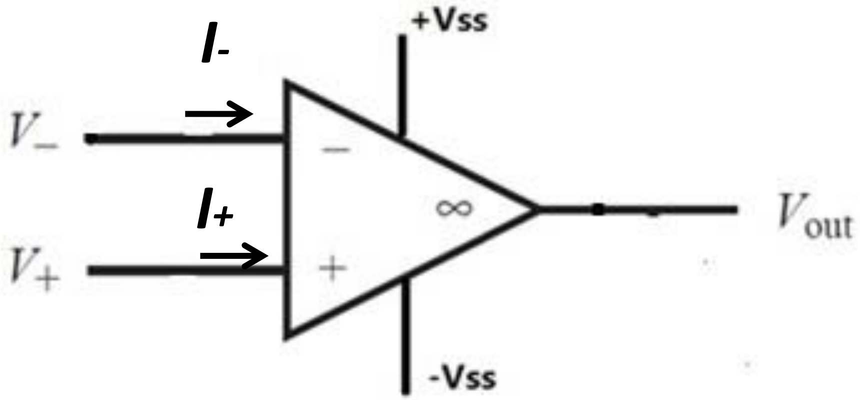
Golden Rule 1:

$$V_+ = V_-$$

What is an Operational Amplifier?

One more characteristic about Op-amp:

It has infinite impedance/resistance at both inputs



Golden Rule 2:

$$I_+ = I_- = 0$$

What is an Operational Amplifier? (sum up)

An operational amplifier is a DC-coupled high gain electronic voltage amplifier with a differential input and usually, a single-end output. (Wikipedia)

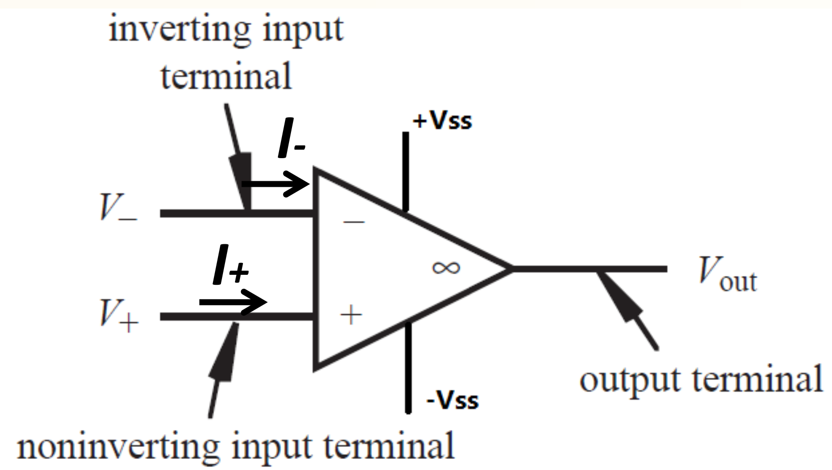


Fig.2. Op-amp schematic representation (open-loop)

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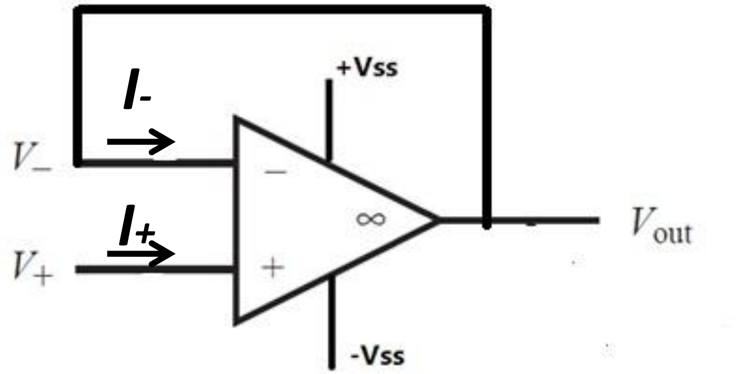

Fig.3. Op-amp schematic representation (closed-loop)

$$V_{out} = \begin{cases} +Vss & V_+ > V_- \\ -Vss & V_- > V_+ \end{cases}$$

Golden Rule 2:

$$I_+ = I_- = 0$$

Golden Rule 1:

$$V_+ = V_-$$

Golden Rule 2:

$$I_+ = I_- = 0$$

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Op-amp application example

E. g.

$V_1 \rightarrow \boxed{0.5} \rightarrow V_2=0.5V_1$

$V_2 \rightarrow \boxed{0.5} \rightarrow V_3=0.5V_2$

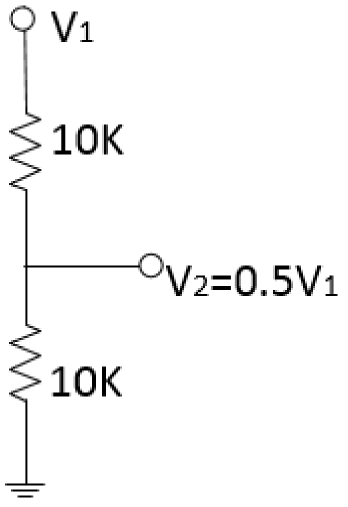
After connecting, we hope $V_3=0.25V_1$

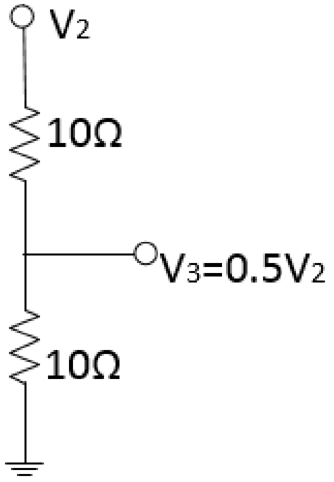
$V_1 \rightarrow \boxed{0.5} \xrightarrow{V_2} \boxed{0.5} \rightarrow V_3=0.25V_1$

Really?

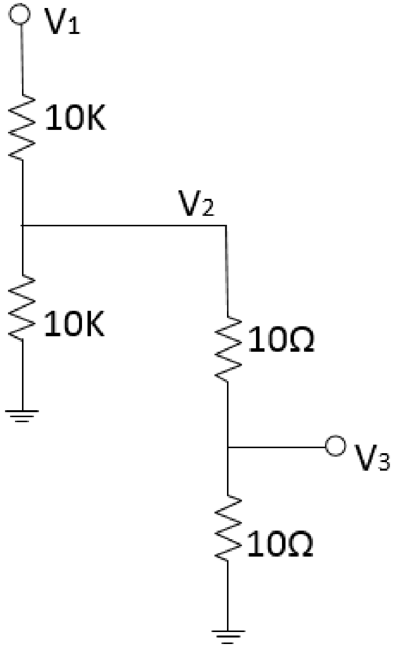
Op-amp application example

E. g.





If connected



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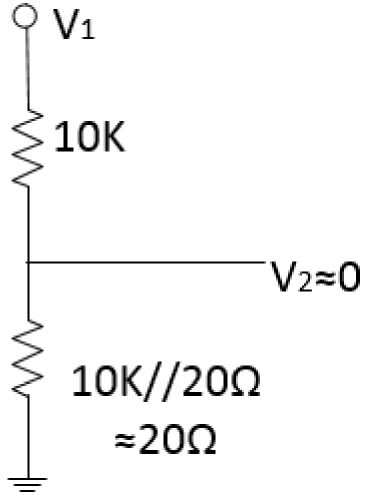
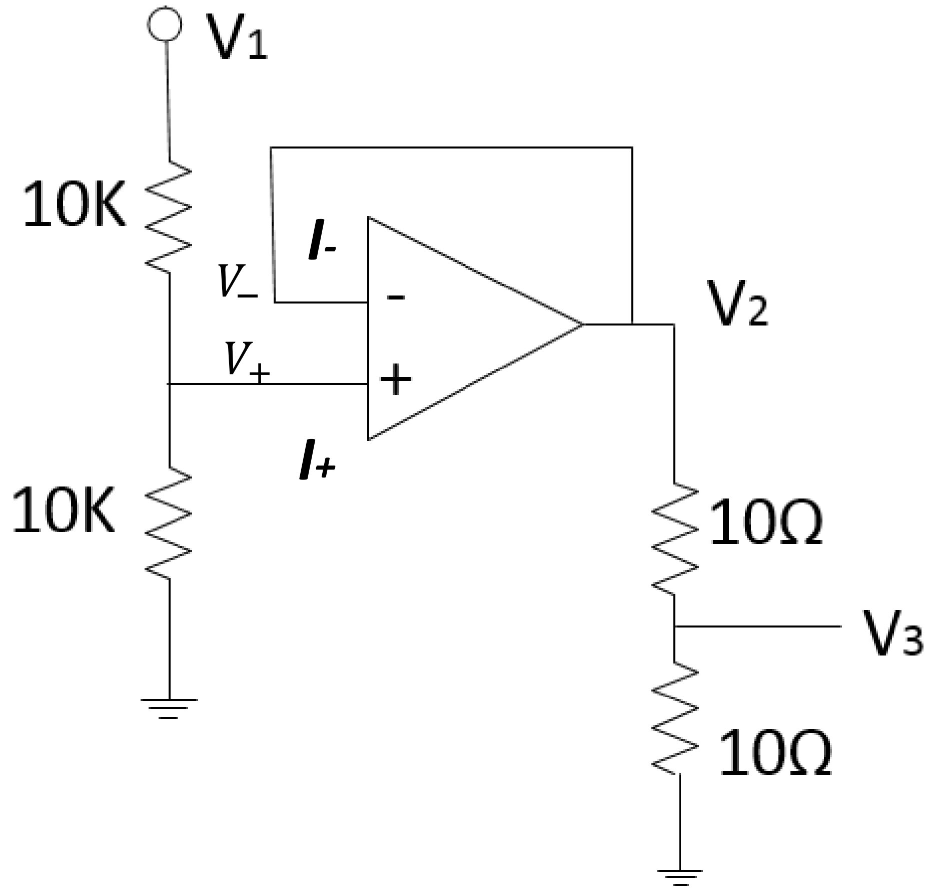


$V_3 \approx 0$

Solution



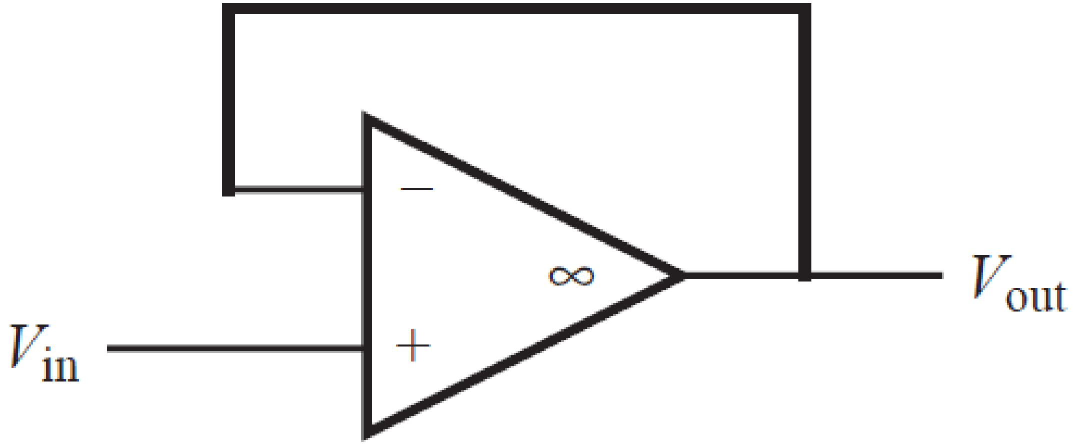
Golden rules:

$$V_+ = V_-$$

$$I_+ = I_- = 0$$

Op-Amp Application

1. Buffer or follower



$$V_{in} = V_{out}$$

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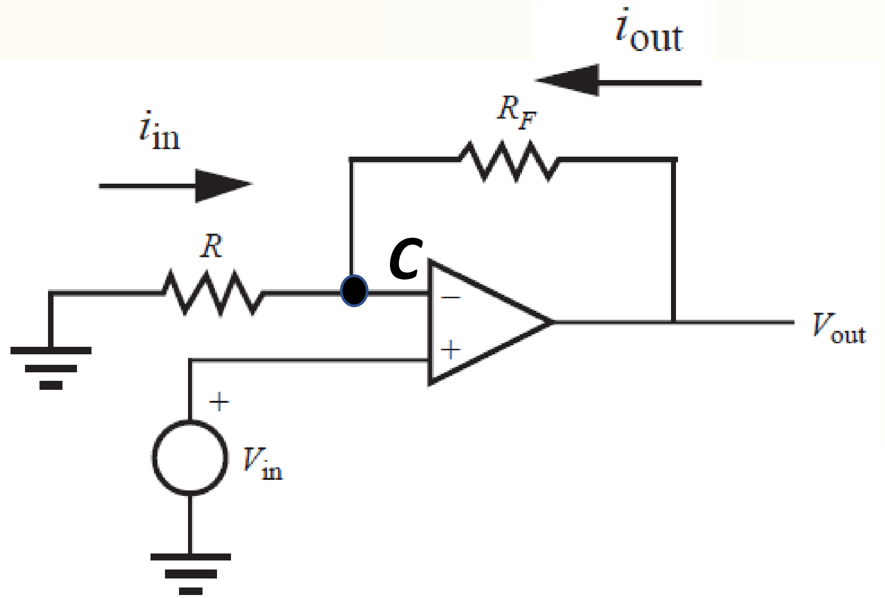
Op-Amp Application

2. Non-inverting op-amp



Golden rules:

$$V_+ = V_-$$

$$I_+ = I_- = 0$$

Ohm's law

Kirchhoof's current law (KCL)

Step 1: Ohm's law to *R* and Golden Rule 1

$$i_{in} = \frac{-V_{in}}{R} \tag{4.1}$$

Step 2: Ohm's law to R_F Golden Rule 1

$$i_{out} = \frac{V_{out} - V_{in}}{R_F} \tag{4.2}$$

Step 3: Rewrite Eq. (4.2)

$$V_{out} = i_{out} R_F + V_{in} \tag{4.3}$$

Step 4: Apply Kirchhoff's current law to node C and Gold Rule 2

$$i_{in} = -i_{out} \tag{4.4}$$

Step 5: Combine Eq. (4.1) with Eq. (4.4)

$$V_{in} = i_{out} R \tag{4.5}$$

Step 6: Use Eq. (4.3) and Eq. (4.5)

$$\frac{V_{out}}{V_{in}} = \frac{i_{out} R_F + V_{in}}{V_{in}} = \frac{i_{out} R_F + i_{out} R}{i_{out} R} = 1 + \frac{R_F}{R} \tag{4.6}$$

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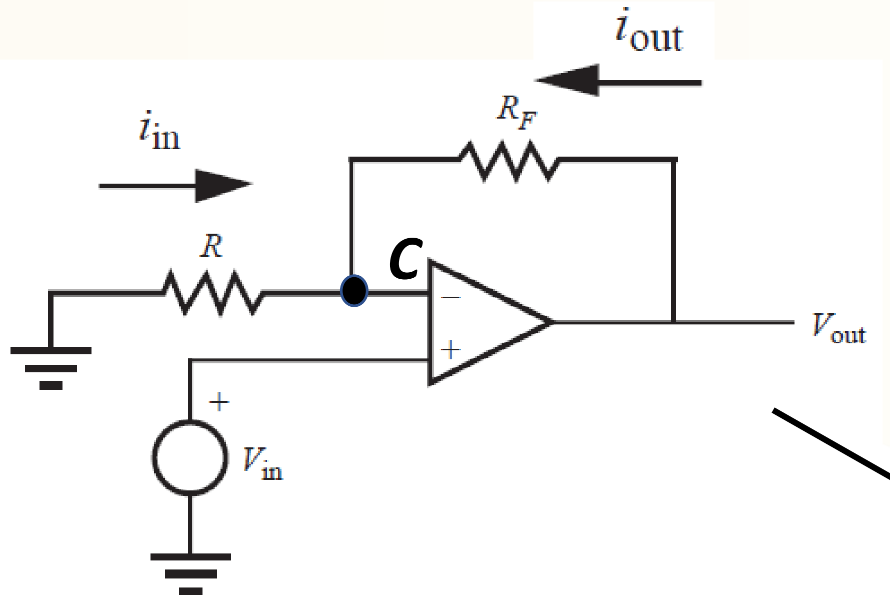
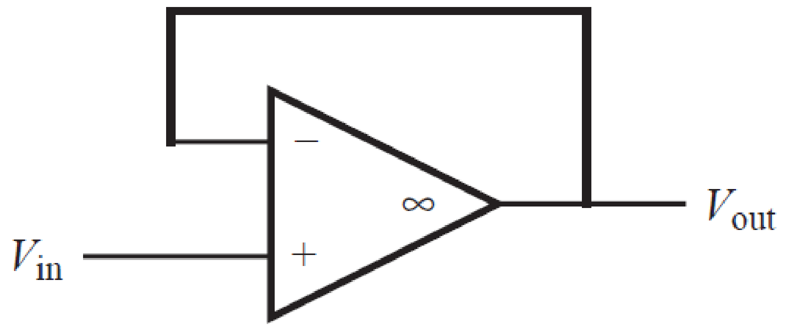
Op-Amp Application

2. Non-inverting op-amp



$$\frac{V_{out}}{V_{in}} = \frac{i_{out} R_F + V_{in}}{V_{in}} = \frac{i_{out} R_F + i_{out} R}{i_{out} R} = 1 + \frac{R_F}{R}$$

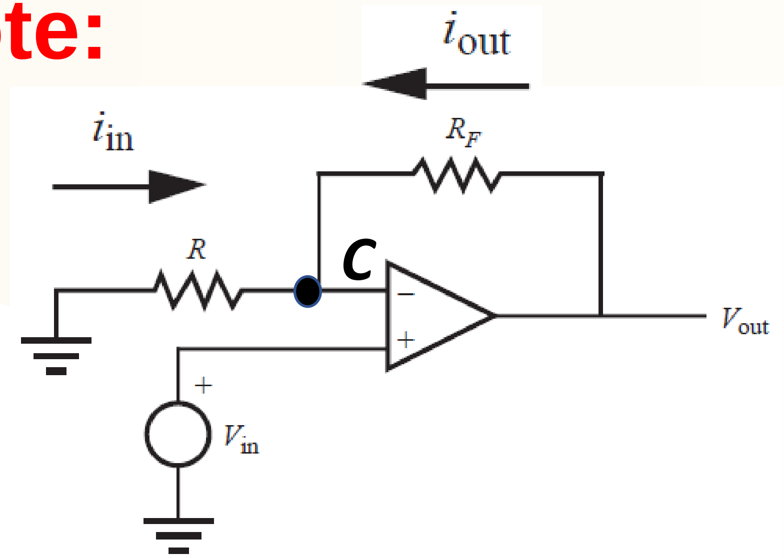
What will happen if R_F=0, and R is very large?



Buffer/follower

Op-Amp Application

Note:



Step 1: Ohm's law to *R* and Golden Rule 1

$$i_{in} = \frac{-V_{in}}{R} \quad (4.1)$$

Step 2: Ohm's law to *RF* Golden Rule 1

$$i_{out} = \frac{V_{out} - V_{in}}{R_F} \quad (4.2)$$

Step 3: Rewrite Eq. (4.2)

$$V_{out} = i_{out} R_F + V_{in} \quad (4.3)$$

Step 4: Apply Kirchhoff's current law to node C and Gold Rule 2

$$i_{in} = -i_{out} \quad (4.4)$$

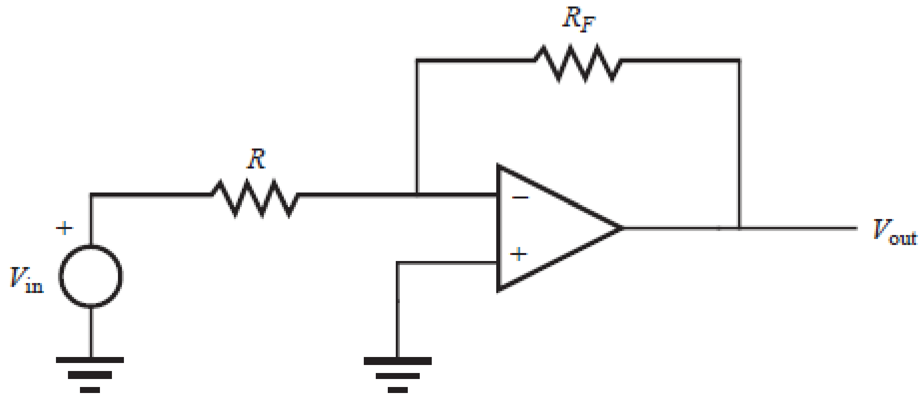
Step 5: Combine Eq. (4.1) with Eq. (4.4)

$$V_{in} = i_{out} R \quad (4.5)$$

Step 6: Use Eq. (4.3) and Eq. (4.5)

$$\frac{V_{out}}{V_{in}} = \frac{i_{out} R_F + V_{in}}{V_{in}} = \frac{i_{out} R_F + i_{out} R}{i_{out} R} = 1 + \frac{R_F}{R} \quad (4.6)$$

Practice



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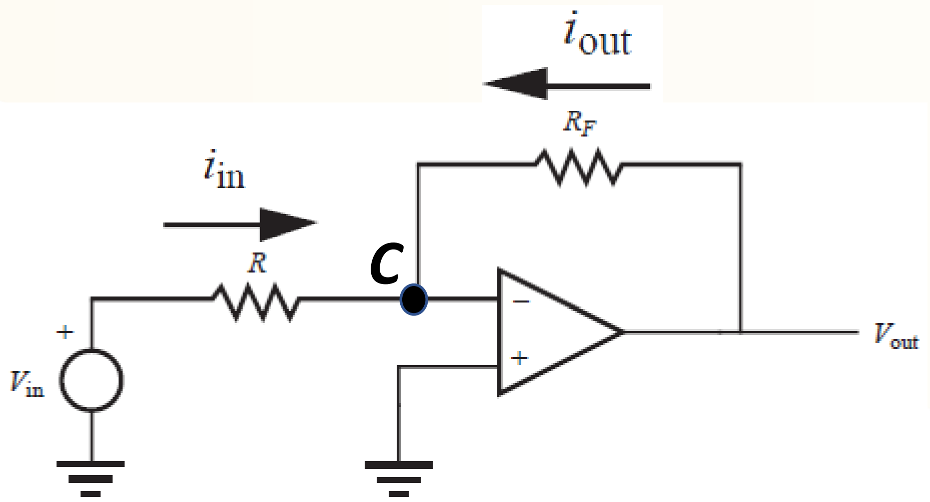
Op-Amp Application

3. Inverting op-amp



Golden rules:

$$V_+ = V_-$$

$$I_+ = I_- = 0$$

Ohm's law

Kirchhoof's current law (KCL)

Step 1: Apply Kirchhoff's current law to node C and with Golden Rule 2

$$i_{in} = -i_{out} \quad (4.7)$$

Step 2: Golden Rule 1

$$V_C = 0 \quad (4.8)$$

Step 3: Ohm's law to *R*

$$V_{in} - V_C = i_{in} R \quad (4.9)$$

Step 4: Ohm's law to R_F and combine Eq.(4.7)

$$V_{out} = -i_{in} R_F \quad (4.10)$$

Step 5: Combine the last two equations

$$\frac{V_{out}}{V_{in}} = -\frac{R_F}{R} \quad (4.11)$$

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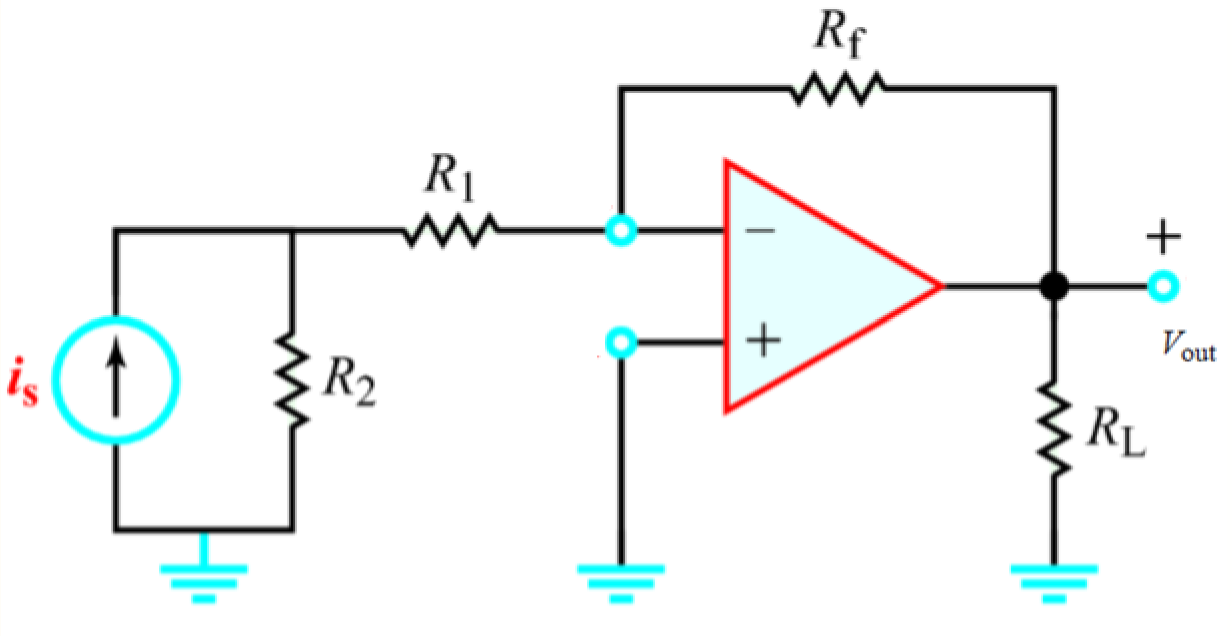
Op-Amp Application

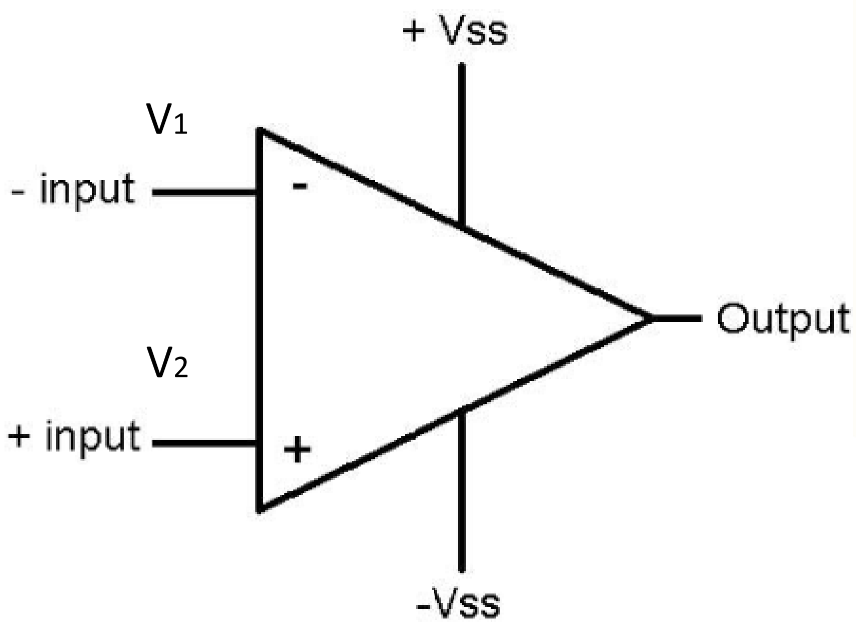
Practice

Given i_s=1mA, R_1=1kΩ, R_2=2kΩ, R_f=30kΩ, R_L=10kΩ, determine V_{out}



Op-Amp Application(open-loop)

4. Comparator

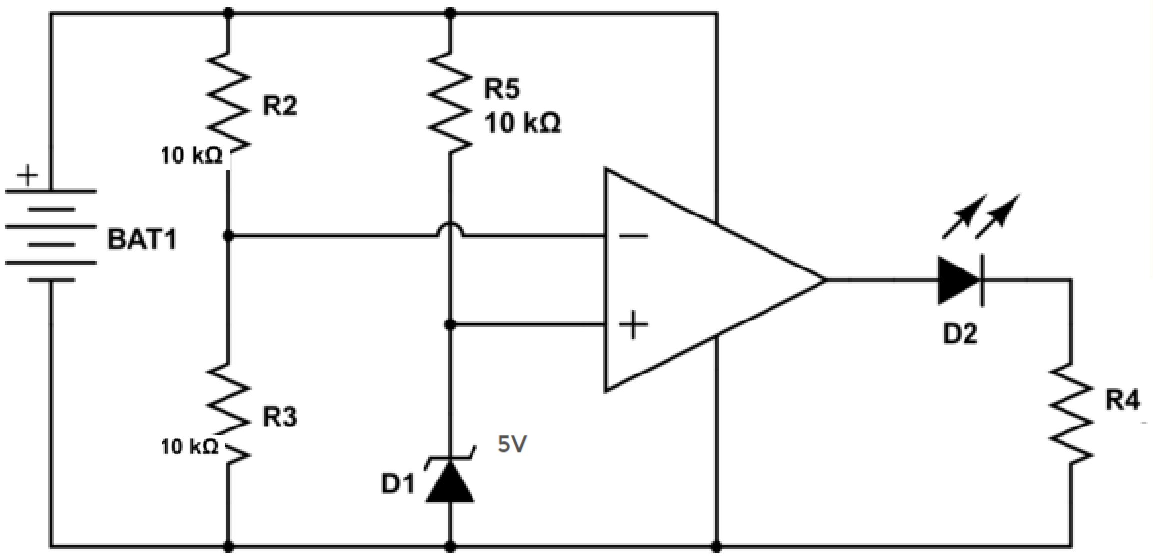


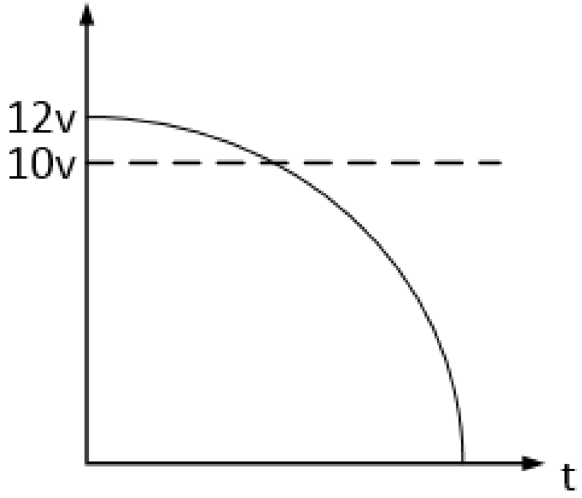
$$V_{out} = \begin{cases} +V_{ss} & V_2 > V_1 \\ -V_{ss} & V_1 > V_2 \end{cases}$$

Op-Amp Application

4. Comparator

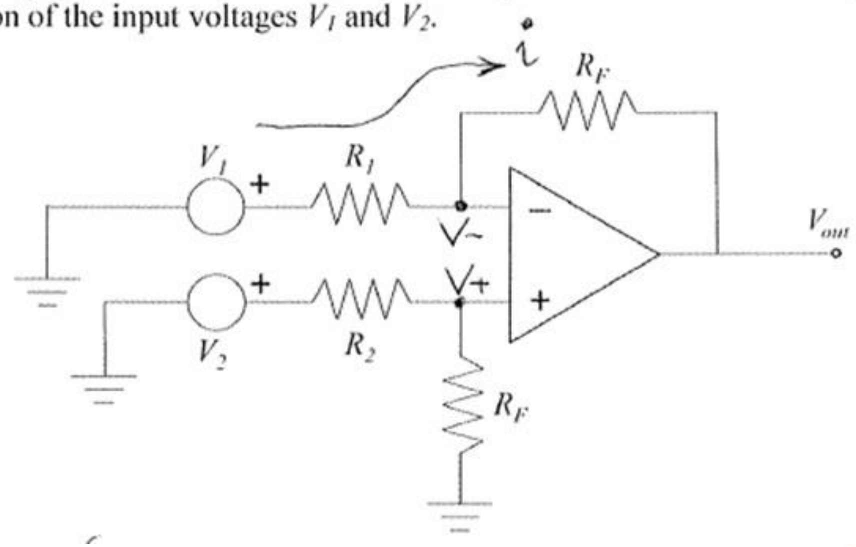
E.g. Low Battery indicator





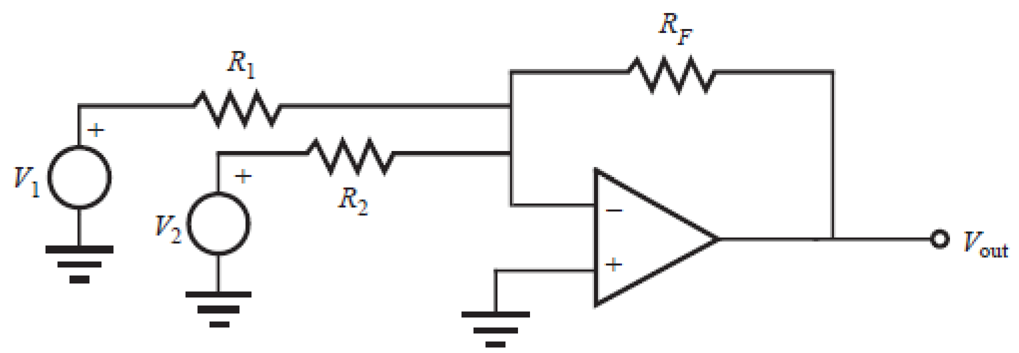
Op-Amp Application (Practice)

The following is the schematic of a difference amplifier circuit. Find the output voltage V_{out} as a function of the input voltages V_1 and V_2.



Op-Amp Application

5. Summing Op-Amp



$$V_{out} = -\frac{R_F}{R_1}V_1 - \frac{R_F}{R_2}V_2 \qquad (4.11)$$

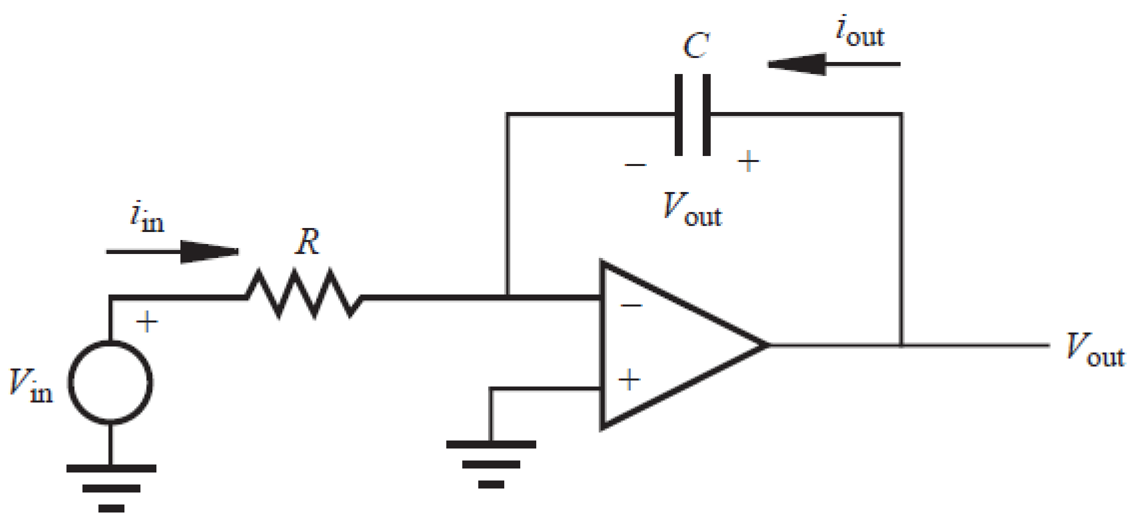
Golden rules:

$$I_+ = I_- = 0$$

$$V_+ = V_-$$

Op-Amp Application

6. Integrator



$$\frac{dV_{out}}{dt} = \frac{i_{out}}{C} \qquad (4.12)$$

$$V_{out}(t) = \frac{1}{C}\int_0^t i_{out}(\tau)\,d\tau \qquad (4.13)$$

Since $i_{out} = -i_{in}$ and $i_{in} = V_{in}/R$,

$$V_{out}(t) = -\frac{1}{RC}\int_0^t V_{in}(\tau)\,d\tau \qquad (4.14)$$

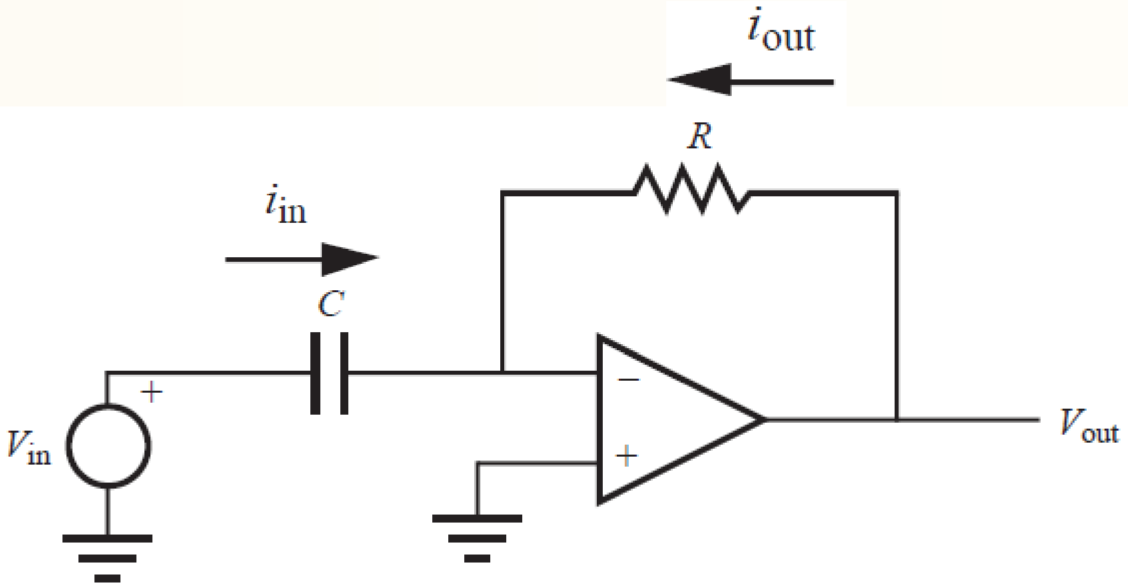
Golden rules:

$$I_+ = I_- = 0$$

$$V_+ = V_-$$

Op-Amp Application

7. Differentiator



$$\frac{dV_{in}}{dt} = \frac{i_{in}}{C} \quad (4.13)$$

Since $i_{in} = -i_{out}$ and $i_{out} = V_{out}/R$,

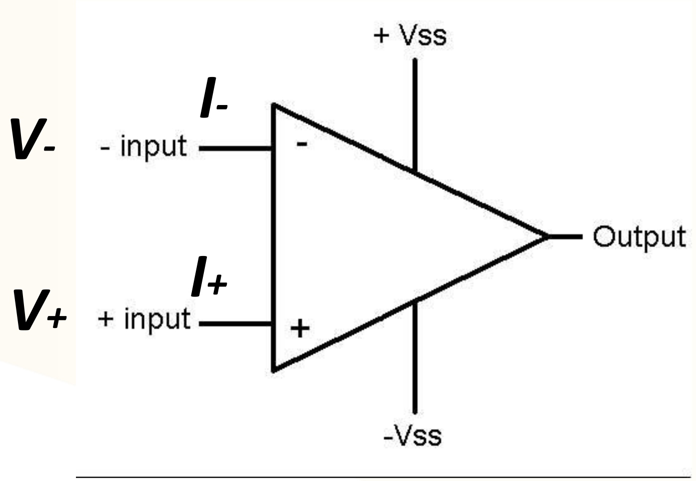
$$V_{out} = -RC\frac{dV_{in}}{dt} \quad (4.14)$$

Golden rules:

$$I_+ = I_- = 0$$

$$V_+ = V_-$$

Summary



Golden rules:

$$I_+ = I_- = 0$$

$$V_+ = V_-$$

Kirchhoff's Current Law

Electronic component characteristics